VOLUME XXVIII NUMBER 3

THE

JOURNAL OF GEOLOGY

APRIL-MAY 1920

COMPILATION AND COMPOSITION OF BITUMINOUS COALS

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A seam or bank of ordinary bituminous coal is readily seen to be stratified; likewise a block or chunk of the same is seen to be highly laminated, and found to be compiled of various layers and sheets of coal differing from one another in color, texture, and fracture, and varying greatly in thickness.[1]

There are generally recognized and described by various authors two kinds of coal with respect to its texture: compact coal and mineral charcoal or mother-of-coal. The former forms by far the larger and the more important part, while the latter forms but a very small, but on account of its nature a conspicuous part of the coal. The mineral charcoal will be considered as unimportant and only incidentally in this paper.

In the compact coal, in general, two kinds of layers are recognizable, apparently alternating and standing in sharp contrast to one another. The one is of a jet-black, pitchy appearance, more compact, and breaking with a concoidal fracture. The other is somewhat grayish in color, of a dull appearance, less compact, and

[1] The figures mentioned in this article are arranged on plates at the end of the article. See Explanation of Plates, p. 206.

breaking with a rather irregular fracture. The former is generally designated as "bright coal" or "glanz coal," and the latter as "dull coal" or "mat coal." On a more careful examination, it is seen that the "bright coal" consists of lenticular masses, greatly varying in breadth and thickness and entirely surrounded by or imbedded in the "dull coal."

It is further found that the "dull coal" is extensively sublaminated into thinner sheets of "bright coal" and "dull coal"; and again on a more minute examination, the bright coal layers are found to be embedded in the dull coal.

The distinction between "bright coal" and "dull coal" has been recognized since the close of the eighteenth century, and many theories have been advanced since that time to explain the phenomenon, but a satisfactory explanation and a true meaning of the alternating dull and bright layers and laminae has never been given.

A condition prevailing generally in all ordinary bituminous coals is well illustrated in Figure 1, representing a small chunk of Illinois coal. In this lump, the "bright coal" is represented by uniform black bands *a*, while "dull coal" is represented by the lighter, finely striated bands *d*. In this respect all ordinary, bituminous coals, no matter from what locality they may be chosen, are similar. Some, of course, like the coal from the Vandalia mine, near Terre Haute, Indiana, possess a larger proportion of "bright coal." Others again, like the coal from the Pittsburgh seam, show a larger proportion of "dull coal"; some seams are all "dull coal," but these are only differences in degree and not in kind.

The sublamination of the "dull coal" is much better illustrated in a vertical fracture slightly magnified, say ten diameters, and especially when such a surface is first smoothed and polished (Fig. 2). The very best illustration, however, is to be had from a thin section, by means of transmitted light and at a low magnification, provided a large enough section is available (Figs. 7 and 10).

Figure 2 represents a part of the surface of the block just shown, limited by the intersecting lines x–x', y–y', m–m', and n–n' and magnified 10 diameters. The bands *a*-1, *a*-3, *a*-5, and *a*-7 represent

"bright coal," and the bands *d*-2, *d*-4, *d*-6, and *d*-8 represent "dull coal." The lettering in Figure 1 and Figure 2 correspond. It may readily be seen that the bands of "dull coal" are compiled of thin black strips which have a black glistening appearance in the coal, interlayered by a lighter-colored matter which has a dull grayish appearance in the coal and is of a rather uniformly granular nature.

All ordinary bituminous coals thus far examined are similar in this respect and any coal might have been chosen equally well to illustrate this condition.

THE "BRIGHT COAL"

Since the term "bright coal" or its equivalent "glanz coal" is applied to a definite component in coal and has become permanently embodied in the literature, the matter must be treated as a separate subject. In speaking of "glanz coal" or "bright coal" it becomes necessary to limit this designation to those bands or components easily recognizable with the unaided eye, such as are designated by *a* in Figures 1 and 2. Such a limitation draws an arbitrary line between the larger bands easily visible and the thinner ones not so easily distinguishable, and comprising a part of the "dull coal" as already indicated. There is no hard-and-fast line between the two. It is with this restriction that the concept of "bright coal' or "glanz coal" is used at this time.

The question that is constantly raised and that must be definitely answered is, "What are the bands of "bright coal" and what is their origin?" In an examination of Figure 1, although representing but a small piece of coal, it will be seen that a number of the bands of "bright coal" taper off on one end. When a larger block is examined many more will be found to do the same and several may be found to taper off on both ends; and when a very large block or a bank of coal is examined closely almost all, if not all, of the bands of "bright coal" are found to taper off on either end. It may be necessary to follow some of the bands for a considerable distance, many feet possibly, but eventually they terminate in a similar manner. Finally when these are examined in all lateral directions, it can be shown that they taper off in all

directions and hence are lenticular bodies and definite components, and are in reality not layers in the strict sense but lenticular masses.

These components vary, of course, greatly in size and form. Their lateral dimensions may range, as already intimated, from a few millimeters to that of many feet; and in shape may range from that of being approximately equilateral, oval, or circular to that of being many times longer than wide. They are all relatively thin, ranging from a thickness barely visible to that of several inches. But strips of a thickness of more than one or two inches are rare and even such of thicknesses approaching one inch are by no means frequent.

"Bright coal" is anthraxylon.—It is not difficult to show that the so-called "bright coal" are components that are derived from the woody parts of plants, parts that at one time were largely composed of wood. Thin sections were cut, both cross-wise and parallel to the bedding planes, from a considerable number of bands of bright coal from a number of different beds and were examined with the view of determining their origin. Every one examined proved to be derived from some woody plant tissue, either of stem, branch, or roots. In every one the cell structure was well-enough preserved so as to leave no doubt as to its origin. "Bright coal" has yet to be found in which no trace of cell structure is observable.

A good example, representing average conditions of the cell structure is shown in Figures 3 and 5. These photographs represent cross-sections of the woody fibers, or, as it is often called, sections across the grain. It will be noticed that the walls have collapsed and are pressed very intimately together, but that the actual mass of the cell walls has retained most of its original matter. There is, however, a considerable variation in this respect in different components and even in the same components, as is shown in Figure 3. In the upper part of this photograph the cell walls have retained most of their original mass, while those shown in the lower part have become thin and in spots poorly definable, a large part of the cell walls having vanished. In some pieces the remaining tissue resembles that of well-preserved sound wood, except that the walls have collapsed; in other cases again the remaining structure is barely recognizable; the whole tissue has

become homogeneous and the lumena and the middle lamella have been effaced. All possible degrees of preservation may be seen between these two extremes.

There can, therefore, be no doubt that the bright coal represents components derived from larger pieces of woody tissues, such as fragments of stems, branches, and roots now compressed and flattened. In some cases these must have been of considerable size. As it is derived from woody tissues (pieces of wood turned into coal) and consists of definite units easily distinguishable from the rest of the coal, it will be called "anthraxylon," from the Greek *anthrax*, coal, and *xylon*, wood. Bright coal then is synonymous with anthraxylon.

THE "DULL COAL"

Having disposed for the present of the "bright coal" or larger anthraxylon components, closer attention may now be given to the so-called "dull coal" in which the "bright coal" appears to be embedded. It has already been shown when seen in cross-section, that it consists mainly of two kinds of material; thin black bands interlayered by a lighter-colored granular-appearing matter (Figs. 1 and 2). The "dull coal" may, therefore, conveniently be divided into two classes: the thin black strips and its embedding matrix, the attritus.

The dull coal as seen in horizontal cleavage surfaces.—When horizontal cleavage surfaces of any compact coal are examined, a varying number of patches showing woody structures are observed to be distributed over the entire surfaces, surrounded more or less by structureless areas (Fig. 4). These patches vary considerably in size, form, and number. But usually they are relatively small and vary within certain limits. This condition is best illustrated in Figure 4, representing a cleavage surface of the coal from the Vandalia mine, near Terre Haute, Indiana. It represents a horizontal fracture through perfectly compact coal and only a very few of the patches seen represent mineral charcoal. Since this coal splits very readily in any desired plane, very many thin sheets may be obtained and thus many horizontal cleavage surfaces may be produced for observation. All reveal appearances very similar

to the one represented. It will be noticed that the woody patches, about one-half natural size in the photograph, are all relatively small and that in many cases the sides running parallel to the direction of the wood fiber form approximately straight lines, while the sides cutting across the fibers are irregular. Rounded and very irregular patches are not uncommon. The condition so clearly expressed in the Vandalia coal is common, in a more or less varying degree, to all the ordinary bituminous coals thus far examined. The example given may, therefore, well serve as a representative type common to all ordinary bituminous coals.

The patches are solid components.—The question at once arises, Are the woody patches, universally seen on the horizontal cleavage surfaces, merely the impressions of some woody fragments that have long since disappeared or are they actual constituents or components of the coal?

It is not difficult to show that the woody patches represent solid masses on the one or the other side of the cleavage surface. There is, however, for each such component a counterpart patch in the corresponding cleavage surface, which is an impression. On cutting with a fine, sharp tool into the patch representing the component, a thin glistening layer of coal is found immediately underneath the surface over the entire patch. Also when a lump of coal is submitted to Schulze's maceration reagent for a certain length of time it may be brought into a condition in which it readily separates into numerous thin, scaly fragments. Many of these bear the woody structure on both sides and when broken show glistening, glassy, jet black coal in the interior. Or, after a treatment for a certain length of time with this reagent, a small lump of coal may be dissected and there may be isolated small sheets or scalelike masses bearing woody marks on the surfaces and consisting of bright glistening coal in the interior.

In splitting a lump of coal it is very rare that the fracture runs through the middle of these thin components, but almost always along one of its surfaces. The larger components of bright coal or larger anthraxylon elements, on the other hand, almost always split through the interior, exposing glistening jetty coal of the same appearance as that in the thin components.

The components seen as patches in the horizontal cleavages and the thin black bands seen in the vertical sections are identical.—The next question arises, "Are the components seen as patches on the horizontal cleavage surfaces as shown in Figure 4 and the black, thin bands seen in cross-sections of the 'dull coal' as shown in Figures 1 and 2, and Figures 7 and 10, identical?" This question can also be definitely answered in the affirmative. A piece of coal, small enough to be placed under a dissecting microscope, may be split horizontally with a sharp tool through any desired lamina; and when thus carefully manipulated it may easily be shown that the black bands seen in the cross-section are the thin, flat components seen on the horizontal cleavage surfaces.

The thin black bands are anthraxylon.—On account of the woody structure present on the surfaces of these components, it must at once be inferred that they are also derived from fragments of woody tissues. The correctness of this inference must be demonstrated so as to leave no doubt.

Correlation of opaque sections with thin sections.—In order to make the demonstration easier and more convincing it is desirable to correlate the appearance of the opaque surfaces of the coal, either at macroscopic observation or at a low magnification in which the characters have already become familiar, with the appearance of thin sections observed by means of transmitted light.

Figure 7 represents the appearance of the cross-section of "dull coal" of an Illinois coal as seen by means of transmitted light at a low magnification. This should be compared with Figure 2, previously referred to, taken from an opaque section of the same sample of coal and at the same magnification, but by means of reflected light. The darker bands in Figure 2, which have been shown to be the components seen as patches on the horizontal cleavage surfaces, correspond to the lighter, more homogeneous-appearing bands interlayered by the heterogenous-appearing laminae shown in Figure 7.

Figure 7 shows numerous strips of thin "bright coal." Figure 8 shows a part of the same at a much higher magnification and plainly shows plant structure in all, but particularly in the strip *a*-1.

Figure 9 is a random horizontal section of coal from the same bed showing that woody structure is present everywhere.

The illustrations given represent the average conditions of most coals in which it is not difficult to detect, in any cross-section, plant structures in most of the strips in question. In some coals, like that from the Vandalia mine and that from Buxton, Iowa, it is not so easy to detect structures so readily in cross-sections. In the horizontal sections, however, plant structures are invariably revealed.

The coal from the Vandalia mine near Terre Haute, Indiana, as shown in Figure 10, at a low magnification is compiled of innumerable thin strips separated by very thin layers of attritus. Cross-sections, at a higher magnification, are shown in Figure 11. The bands *a*-1, *a*-3, and *a*-5 represent some of the thin strips seen in Figure 10. There is very little in these that resembles plant structure. In the horizontal sections, on the contrary, no matter where cut, it is clearly shown that these strips still bear a profusion of plant structure as seen in Figure 12. Of all the coals examined the Vandalia coals contain the poorest preserved structures. Similarly in all coals there are many strips in which at a casual observation no or little direct plant structure is noted, but when such specimens are examined in horizontal sections, plant structure is invariably found to be present. There is, nevertheless direct evidence of such structure almost always observable in cross-sections in the great majority of strips. It will be noticed that most of them have a finely striated or fibrous appearance and this structure is due to the remaining plant structure in the strips. This structure becomes recognizable in the horizontal sections and hence is a direct evidence of cell structure.

A large number of horizontal sections have been prepared from a considerable number of coal seams and in every case cell structure still existed in these thin laminae. The evidence may be considered conclusive.

There exists, therefore, little doubt that the thin bands of bright coal forming a large part, and in many the largest part of the dull coal of ordinary bituminous coals, are also derived from the woody parts of plants. But instead of representing larger parts of plants

they represent only small fragments or chips of the same. The thin strips of "bright coal," therefore, are also anthraxylon components.

Origin of the small anthraxylon components.—It is interesting to know why so large a bulk of the coal should exist in the shape of these thin but relatively wide or broad anthraxylon chips. This question is readily and satisfactorily answered by analogous conditions in peat. Furthermore, a study of these chips of wood in peat lends at once, by analogy, a proof of the woody origin of the anthraxylon components in coal and form a picture as to what may have taken place in the peat bogs of the Coal Age.

In examining a peat deposit such as had its origin in an arboreal growth (Fig. 13), it is discovered that a large proportion of the woody matter consists of thin scaly chips, as shown in Figure 14, which may easily be separated from the peat. As shown in Figure 15, they consist of very thin tangential shells and thin radial plates.

The larger stems and branches of the fallen trees while still above the surface of the deposit become partially decayed. The tissues, having thus become very much weaker along the spring wood of the annual growth rings where the cells are large and the walls relatively thin, are apt to separate along this area, peeling off as thin tangential sheets at the slightest disturbance. A semi-decayed stem of the basswood, Tilia Americana, is a well-known example with a tendency to peel off in this way. Sheets of semi-decayed wood of that nature break up very readily into smaller and still thinner chips. Conifers also have a tendency to peel off in this manner. In trees with broad rays like the oak, the weakest areas are formed along planes parallel to the medullary rays and the tissues will separate into thin radial plates instead of tangential scales or shells. Through either mode of disintegration numerous thin and relatively broad plates or scaly chips of semi-decayed wood are formed. These constitute a very large proportion of the peat. A similar mode of disintegration must have taken place in the peat stage of the Paleozoic coals, as the small anthraxylon chips in coal indicate. The chips in coal and the chips of woody peat in peat are similar.

The kinds of tissues represented in the coals.—In an examination of a considerable number of sections from a number of coals, it is learned that by far the larger proportion of the tissues remaining represent woody parts of plants. By woody parts of plants is meant parts of stems, branches, twigs, and roots, including all the tissues, except the bark, that goes to make up such a part of the tree or shrub. It cannot be said with certainty that the bark has contributed to any extent to the constituents in question. If bark is present at all in coal it finds its recognition possibly in components appearing altogether different, which will be discussed later.

The anthraxylon of the dull coal then is derived for the most part from rather small chips of semi-decayed woody tissues, such as are prevalent in the peat bogs of today. Prosenchyma or wood proper, and parenchyma such as cortex, pith, and rays are all met with and are clearly distinguishable. There is, nevertheless, no doubt that some of the structure seen in thin sections is derived from the more succulent or younger parts of plants as well as from herbaceous plants. Leaf-strands with some of the accompanying tissues, petioles, and other vascular strands are frequently detected. What appear to be delicate tissues of plants are frequently seen. The parenchyma of leaves is rarely observed, yet occasionally structures are seen that could be construed as having been derived from leaf parenchyma, and in some cases certain structures represent without a doubt leaf tissues in which all the leaf tissues, particularly the palisade cells, are well represented, and may be favorably compared with the leaf tissues of a living Cycad. In most cases the tissues contained between leaf cuticles have been disorganized beyond identification. Occasionally tissues are found in a fairly good state of preservation which as yet cannot be correctly classified. In this connection spore walls or sporangia should also be mentioned. Sporangial walls, either singly or in connection with remainders of cones, are a common occurrence in most coals, but particularly abundant in the coal from Buxton, Iowa. Such spore walls are often remarkably well preserved. A considerable amount of the woody tissues as well as other plant tissues have been reduced to a finer state of division, exactly as is

the case today in the peat deposits, and hence are classed with the attrition matter and will be discussed under the attritus.

Cuticles.—The outermost layer of tissues of all leaves, petioles, green parts of young stems, twigs, fruit, and seeds of plants, consists of tabular cells very closely united and uninterrupted except by stomatal pores. This is the epidermis. In some plants it persists with but little change; in others it is thrown off sooner or later and replaced by a layer of cork. Delicate epidermis possesses thin walls; but in a large number of plants with fleshy and tough leaves, the walls are of considerable thickness.

The exposed surface of all epidermal cells are covered with a layer of cutin forming a continuous transparent film or membrane over the entire surface of leaf or stem. This film is called the cuticle. It is present on all leaves, pedicles, green or young stems, twigs, fruits, berries, and sometimes persists on older stems and branches. Often the cuticle is further covered with a waxy and resinous matter. In some cases the amount of such substances is large and assumes commercial importance, as in the wax palm (Ceroxylon andicola) and the bayberry (Myrica cerifera). The waxy coatings may be in the form of coherent layers or incrustations upon the cuticle; in crowded vertical rods, sometimes of considerable length; in very short rods or rounded grains, very much crowded on the leaves of some plants; or in minute grains or minute needles.

The cuticle is very resistant to putrifying organisms and persists under peat-forming conditions after most of the underlying tissues have been disorganized or have disappeared. Cuticles or fragments of cuticles are always present in peat, occasionally in large proportions.

Cuticles in coal.—Similarly in coals a large amount of cuticular matter and some cuticularized tissues have survived and are ever-present constituents, often forming very appreciable proportions of the dull coal (Fig. 16).

In thin sections, under the microscope, the cuticles appear as bright golden-yellow bands of considerable length but relatively narrow. One edge is usually smooth while the other is usually saw-edged. Frequently they are found in pairs with the same-edged

sides toward each other. Figure 17 is taken from a section containing a large proportion of cuticular matter very similar to that shown in Figure 16. Here the cuticles are represented by comparatively heavy light-colored bands, sometimes in pairs embedded in a general dêbris derived largely from leaves and other vegetable matter. Cuticles are sometimes accompanied by well-preserved leaf tissues. Cuticular matter is also present in a macerated or more or less fragmented condition. When in this condition it forms a constituent of the attritus, and is often difficultly distinguishable from fragmentary spore-exine matter which it closely resembles in color and general appearance.

Like the spore-exines the cuticles may very easily be separated from the coal by means of Schulze's reagent. When thus separated from the coal they appear as tissues or films constructed of cells (Fig. 18). They are, however, non-cellular, hyaline membranes and the apparent cell structure is due to ridges on the under surface that conformed to the once underlying epidermal tissue. In cross-section these ridges give the saw-edged appearance. A considerable number of patterns of the apparent cell structure, or in other words, different types of cuticles, are found, thus indicating that a number of different species or genera of plants are involved.

BARK

It cannot be said with certainty that bark has contributed any appreciable amount to coal; nothing has been met with that could be referred to with certainty as derived from bark. There is, however, a constituent reoccurring in all coals, most frequently in the coal from the Pittsburgh seam, that might be interpreted as being derived from bark. It is shown in Figure 6. This component is always of a dark-brown color, lumpy, porous, and of irregular structure. By far the largest proportion of it has retained some of its original plant or cell structure. On the whole, the remaining cell structure is very poorly and very irregularly preserved and appears to be derived from large-celled tissues. It almost always includes a large number of resinous-appearing globules, and frequently also more highly carbonized matter. It also frequently includes parts of the tissues, or strands of tissues, in which the plant structure is still well preserved. In some of

the components the whole mass is fairly well preserved and then again, components are met with in which the whole mass is disorganized and consists of irregular fragments, but always of the same color and general appearance. Frequently the component is composed of bands of more or less well-preserved tissues alternating with bands of disorganized, granular matter.

The components vary largely in size as seen under the microscope, ranging from but tiny bits to good-sized masses. There is also a wide range of transparency in them, both in different components and in different parts of the same component. The most transparent ones are of a dark-brown color in thin section, but opaque in medium-thick sections.

This component, possibly derived from bark, is characteristic through its brownish red color in thin section, irregular structure, lumpiness, and relative opacity, and is easily distinguishable from the rest of the coal. Although in some layers or laminae it may be quite abundant, yet, on the whole, it forms but a small part of coal.

The attritus.—It has been shown that the larger anthraxylon components or bands of bright coal are embedded in the dull coal; and in turn that the dull coal consists largely of smaller anthraxylon constituents together with a few other constituents such as cuticles and barklike constituents, embedded in a general matrix, the attritus.

At low magnification, the attritus appears as a uniformly granular, amorphous mass (Figs. 2, 7, and 10). At a higher magnification, it at once appears as a very heterogeneous substance. Typical appearances of the attritus in cross-section are shown at *d*-2 and *d*-4 (Fig. 11); at *d*-1, *d*-3, and *d*-7 (Fig. 19); at *d*-1, *d*-3, and *d*-5 (Fig. 20); and in horizontal section in Figures 22, 24, and 25. A close examination at a high magnification will at once reveal that it is composed of a number of groups or classes of constituents, most of the members of which are specifically and definitely definable and their origin determinable. These are cellulosic degradation products or humic matter, spore-exines, resinous matter, cuticular matter, more highly carbonized matter, certain small bodies usually designated as rodlets or needles, and some mineral matter.

The humic matter, or cellulosic degradation products.—In the photographs just referred to, particularly noticeable at *d*-1 (Fig. 19), there will be recognized besides the strips designated as anthraxylon constituents, other strips similar in appearance but thinner and more irregular in width and bearing no marks of plant structure. Besides these, there are other more globular constituents, some of very small sizes, others very finely divided. These are of the same general appearance and color as the anthraxylon matter and constitute part of the attritus. Most of this matter evidently is of the same general origin as the anthraxylon components, and may be collected into one class and designated under the general term of "humic" matter. Under "humic" matter then is considered the cellulosic degradation products in a state of division finer than the smaller anthraxylon components but not including resinous, cuticular, spore, or carbonaceous matters. There is no hard-and-fast line of distinction between the smaller anthraxylon components and the humic matter. The particles constituting the humic matter in general no longer bear visible marks of plant or cell structures and are smaller in sizes.

It should be emphasized that the humic matter consists very largely of definitely definable particles and not of a vague plastic or homogenous mass, and only a comparatively small proportion is so finely divided as to lose its individuality even under very high magnifications. When this stage is reached, we enter the realm of colloidal conditions, and proper methods will here also show that the matter consists of individual particles.

There must be included in the term humic matter, substances of a wider origin than the anthraxylon, such as gums, pectins, cork, bark, and other substances closely allied to the cellulosic materials. In analagous studies of peat, where the constituents are more easily identified, there is very little matter that is of other origin than cellulosic; and if the formation of coal and peat is to be considered analogous, the conclusion must be drawn that but a small proportion of the humic matter in coal can be other than of cellulosic origin. This, however, does not dispose of a long list of substances known to exist in plants, such as tannins, alkaloids, oils, terpenes, camphors, etc.; but if these or their derivatives are still present

it is very likely that they are present in an absorbed condition; that is, absorbed by the anthraxylon and other constituents, and so will have lost their identity under the microscope. In the peats, many of these substances may be detected by microchemical means, and are found to be absorbed mostly by the woody constituents, but ordinarily are not visible under the microscope.

Since there are no, or at the most very few, plant structures remaining in that part of the coal classed under the attritus, the origin of all its constituents, with the exception of the spore-exines, cuticular matter and certain resinous matter, cannot be as closely defined as the anthraxylon matter. Though much of this matter is clearly shown to be woody degradation products, yet it is highly possible that a considerable amount of bark and cortex is included. As has been stated before, bark, that is, that part of the tree or plant usually designated by that term, has not been recognized positively in the coals examined. Cortex, pith, and parenchyma have been recognized comparatively speaking in small quantities. The conifers of the Paleozoic times probably were the only trees with true bark, and the bark of these undoubtedly disintegrated similarly as that of the peat-forming trees and shrubs of the present, and this largely lost its identity and still exists as humic matter.

The spore-exines.—The spore-exines (Figs. 27–41) are ever-present constituents, and no coal is entirely free from them. Even the coals with the least number of spore-exines, like the Vandalia coal from Indiana, contain a considerable amount of spore matter. Under the microscope, in thin section, they are the most conspicuous objects in the coal, due to their clear yellow color and transparency. In the photographs, representing cross-sections, at a magnification of 200 diameters, they may be recognized as very small linear patches (Figs. 19 and 20). At higher magnifications, say at 1,000 diameters (Fig. 21), their true nature is more clearly shown. Here they appear, when whole, as collapsed rings, being in reality collapsed spheres, and merely represent the outer shells or spore walls or exines of once living spores of the Paleozoic plants that evidently also contributed to the coal themselves. Its contents, such as nuclei, protoplasm, chloroplasts, and inner spore

wall have disappeared completely, or almost so. In the photographs at 200 diameters prepared from horizontal sections (Fig. 22), the spore-exines are shown on their broad side, and appear as circular to oval or slightly triangular disks. At a higher magnification, say at 1,000 diameters (Figs. 24 and 25), the characters, such as form, sculpturing, and tetrasporic marks remaining on the exines, are clearly shown.

An excellent way to study the spore-exines is to macerate the coal by means of Schulze's reagent and digest it with ammonia. The spore-exines and cuticles are left undissolved and apparently unchanged. Figures 27–41 show some of the spore exines thus isolated.

From a collective study of all the spores, it is evident that a considerable number of species and genera of plants contributed to the spore matter in coal. Two distinct types of exines are distinguishable. The one is always in the shape of a circular disk, in some cases tending to be triangular and less often tending to be oval or ovoid, and all bear the familiar tetrasporic mark. These are the exines of Paleozoic Pteridophytes. The other is always oval or ovoid, but does not bear the tetrasporic mark and has a long slit parallel to the long axis of the oval; often with a second short slit at, or toward, one of the extremities. The surface is apparently smooth and unsculptured (Figs. 25 and 30). These are undoubtedly the exines of the pollens of certain Paleozoic Gymnosperms.

The exines of true spores.—On the whole, the true spore-exines are much more abundant in coal than are the exines of pollen grains. There is a large range of sizes among them, from that of only about 10 microns (Figs. 22 and 24) or $\frac{1}{100}$ of a millimeter, to that of 2 and 3 millimeters in diameter (Fig. 38). There are to be recognized two kinds: megaspores and microspores. From a biological standpoint, three kinds should be distinguished: megaspores (Figs. 35 and 38), microspores, and neutral spores. This is not only a distinction of size, but also of function. Megaspores in living plants are always large and on germination produce male gametophytes; microspores are always relatively small and produce female gametophytes; while certain other spores, classed among

the smaller ones, may produce gametophytes that may reproduce either male or female gametophytes, there being apparently no predetermination. Among the spores of the coals, no such distinction can be made, and all that can safely be said is that some are large and others are small, and assume that the larger ones are megaspores; but between the spores that functioned as microspores and those that are neutral, no distinction can be made, and the term microspores must apply to both kinds, if used at all. This affords a convenient, if not exact, distinction, between the very large spore-exines and the smaller ones. It should be stated that the range in sizes is gradual from the smallest to the largest, and that no fast line, in regard to size, can be drawn between the two.

The thickness of the exine walls varies very greatly with the kind of spore from which derived, and ranges from the tinest film of only a few microns in thickness to such where it is a huge mass of a hundred microns or more, as in the large megaspores as shown in Figure 38. But the size of the spore is not always commensurate with its thickness. Very large spores are observed with but very thin walls, and again comparatively small exines are met with which have walls equal in thickness to half their diameter.

Almost all spore-exines are sculptured, and only comparatively few are smooth, and each kind has a definite type of sculpturing, which affords a ready means of distinction between them. The sculpturing may take a variety of forms and may consist of serpentine ridges, irregular elevations, echinate protuberances, sharp, slender spines, and short hairlike coverings. In many cases, these are arranged in definite order, as in spirals or rows (Figs. 27–41). Some exines are covered all over with a ramentum; others bear a long tuft of ramentum on a small area only; others have a number of long slender wings; and still others have three large air sacks.

Exines of pollen grains.—A large number of exines present in coals are apparently those of pollen grains (Figs. 25 and 30). In a very large number, especially noticeable when they have been isolated from the coal by means of Schulze's reagent, there is a long slit running parallel to the long axis of the oval; and

frequently with a short cross slit at or near one of the ends of the longitudinal slit, but a tetrasporic mark is never seen. The absence of the tetrasporic mark and the presence of a slit then are characteristic characters. In color, transparency, and consistency they are similar to the true spore-exines. Their surface is always smooth and has no spines, processes, or hairlike coverings. They vary greatly in size, indicating that a considerable number of species or genera of plants are involved. Compare Figures 25 and 30, photographed at the same magnification.

The resinous matter.—There are universally scattered through or contained in the attritus of all coals, certain particles, which, when seen under the microscope, are generally of a more or less rounded or ovoid form, rarely angular or irregular; of a rather homogeneous or vitrious consistency; of a brownish red to red color, a color very similar to that of the anthraxylon components and the humic matter, called resinous particles. Such form a very appreciable part of many coals. These constituents are classed under resinous matter, because they resemble very closely certain constituents in peat and lignite where they are more certainly known to belong to the natural resinous substances of plants. Many of the resinous-appearing bodies in the attritus, moreover, very closely resemble certain bodies still included in the original tissues of both the smaller and the larger anthraxylon components. Further, there are clear cases of transition from where they are still included in the original tissues to that where they are free in the attritus.

There is, therefore, enough basis for assuming that the constituents in question are derived from the natural resins of the Paleozoic plants. The proof is, nevertheless, not as positive as one would like to have it. But since the constituents in question stand in quite sharp contrast to the other constituents and are tolerably well definable into a distinct class of components, the term applied to them is believed to be justifiable. Besides, it affords a convenient means to distinguish them from the other constituents.

Good illustrations of resinous matter in the attritus are given in Figures 23 and 26, also in Figure 19. Figure 26 shows

exceptionally large amounts of it, but layers with equal amounts are not rare in any coal.

The carbonaceous matter.—All ordinary bituminous coals contain certain constituents that are more highly carbonized than the rest of the coal and to which it stands out in sharp contrast on account of their opaqueness. These are well represented in Figure 22, in which these constituents are represented by the more or less irregular black areas. They are also seen in Figures 19 and 20, 21, 24, and 25.

In general, there are two types of carbonaceous matters: one shows definite plant structure and is clearly shown to be more highly carbonized parts of plant cells or bits of woody or other plant tissues, and the other shows no plant structure and is of indefinite origin.

The former usually have retained the original plant form and characters, such as pores, pits, trabacular and spiral thickenings. These are nothing more or less than smaller bits of mineral charcoal. The different constituents of this class of carbonized matter vary largely in the degree of carbonization and hence also in opaqueness. Its opaqueness varies from that where it is only slightly more opaque than the normal anthraxylon constituents to that where it is entirely opaque even in the thinnest sections. In general, however, most of it is opaque in the medium thin sections, becoming translucent in the thinner sections. Relatively very few appear to be entirely opaque in the thinnest sections. When translucent or transparent, they are of a dark-red color, becoming darker with increase of opaqueness and of a lighter red with decreasing opaqueness, approaching a pale yellowish red in color.

The disorganized opaque matter.—The other kind, the disorganized and more irregular kind of opaque matter, is not so easily defined. Its origin is possibly varied, but most of it is of undoubted organic origin. The shape of most of the particles comprising the matter is irregular, but a considerable number are oval to spherical. In size they vary from the most minute particle to that visible to the naked eye. The more spherical and oval particles suggest carbonized resinous matters.

Rodlets.—Other constituents that are invariably present in all coals are the so-called rodlets. Generally speaking, they form

but a small part of any coal, but they are much talked about on account of their conspicuousness and prominence in the mineral charcoal and on the cleavage surfaces. They are called rodlets because they have the appearance of minute rods. By some they are also called needles, because of their slender needle-like appearance. In cross-section, the rodlets appear as circular to oval disks of a dark color in very thin sections; in thicker sections they are opaque. They are of a relatively large size when compared with spores and pollen grains.

Many of the rodlets are scattered helter-skelter through the attritus (Fig. 43). In some laminae they are present in large numbers, and in such cases, form a large proportion of the coal. Many of the anthraxylon components (Fig. 44), and, conspicuously, many of the mineral charcoal constituents, inclose many rodlets that are evidently part of their structure or tissue. Some of the tissues in coal with which rodlets are associated may be classified with the Medullosae (Fig. 44), well-known Paleozoic plants allied to the Gymnosperms. The cortex of the Medullosae is known to have been pervaded by gum or mucilage canals. In a specimen at hand of Medulosa Anglica (Fig. 42), these canals are still filled with a dark solid substance. These solids resemble very closely certain rodlets embedded in the attritus, as well as those associated with anthraxylon components.

The rodlets are non-resinous, give off a blue non-sooty smoke on burning, do not swell or puff up, and do not become viscous when heated. They are of a black, glistening, glassy consistency, breaking with a decided concoidal fracture. When burned, they leave a very delicate, finely grained skeleton of quarts, the relative amount of which varies very largely in different rodlets. In some it forms a very delicate skeleton, while in others there remains a solid mass almost as compact as was the rodlet before burning, except that it is now snowy white. Between these two extremes, all possible intergrades may be observed. In fact, some rodlets consist of almost pure white quartz. Some have a core of quartz surrounded by a shell of black matter.

It seems clear then that some of the rodlets, if not all, are the semi-petrified or petrified contents of the mucilage canals of certain Cycadofilicales, like Medullosa.

SUMMARY

The bituminous coals consist of alternate layers of "bright" coal and "dull" coal. The "bright" coal is called anthraxylon.

The "bright" coal was formed from the large limbs and trunks of trees or parts of them which were not disintegrated in the peat swamps previous to the formation of the coal. This "bright" coal retains its original woody structure, although often somewhat distorted.

The "dull" coal consists of numerous small layers or chips of "bright" coal embedded in a dull matrix, the attritus. These small chips of anthraxylon are derived from the chips, splinters, small stems and branches, twigs, roots, etc. Possibly part of the large woody chunks slightly disintegrated, due to the incipient decay previous to the formation of the coal, and thus provided some of the small layers of "bright" coal. No bark entered into the formation of the small layers of anthraxylon.

The dull matrix or attritus, in which the small layers of "bright" coal are embedded in the "dull" coal, was derived from the following sources:

a) The waxy cuticle covering of the leaves. This is an extremely resistant substance and remains in the coal in narrow, yellowish, semi-transparent bands of varying lengths.

b) Spore-exines. These vary from 0.01 mm. to 3 mm. in cross-section.

c) Pollen exines.

d) Resinous matter. This is the original resinous substance of plants.

e) Small particles of resinous and woody matter from a highly carbonized state down to a little carbonized state.

f) Small rodlets or needles. These are possibly the petrified or semi-petrified gum or mucilage canals that pervaded the cortex of some Paleozoic plants. On burning, they leave a white quartz skeleton.

g) Small amounts of gums, pectins, and corks.

The tannins, terpenes, alkaloids, etc., if still present, are absorbed in the coal and do not show up microscopically.

EXPLANATION OF PLATES

PLATE III

FIG. 1.—A block of Illinois coal from vein No. 6. The black bands *a* represent anthraxylon, the grayish bands *d* represent the layers of "dull coal." The area described by the intersections of the lines *x–x′*, *y–y′* and *n–n*, *m–m′* is the same area shown in Figure 2, and bands *a*-1, *d*-2, *a*-3, *d*-4, *a*-5, *d*-6, *a*-7, and *d*-8 of the one are correspondent to the other. The lenticular band "CO" represents a cone of Lepidodendron. Natural size.

PLATE IV

FIG. 2.—The area described by the lines *x–x′*, *y–y′* and *n–n′*, *m–m′* in the block of coal shown in Figure 1, and enlarged 10 times. The bands *a*-1, *d*-2, *d*-4, *a*-5, *d*-6, *a*-7, and *d*-8, representing alternate layers of anthraxylon and "dull coal," of the one being correspondent to the other. ×10.

PLATE V

FIG. 3.—A part of a thin cross-section of "bright coal," or anthraxylon, showing more or less well-preserved structure of wood. ×200.

FIG. 4.—A horizontal cleavage surface of compact coal from the Vandalia mine near Terre Haute, Indiana, showing patches with woody structure or anthraxylon chips, more or less surrounded by structureless areas representing the attritus. "Needles" are also shown. ×200.

FIG. 5.—A part of a thin cross-section of "bright coal," or anthraxylon, with resinous inclusions. ×200.

FIG. 6.—Part of a thin cross-section of coal from the Pittsburgh seam, consisting of a constituent that may be bark. The tissue is large-celled, irregularly preserved, including a considerable amount of resinous matter. ×200.

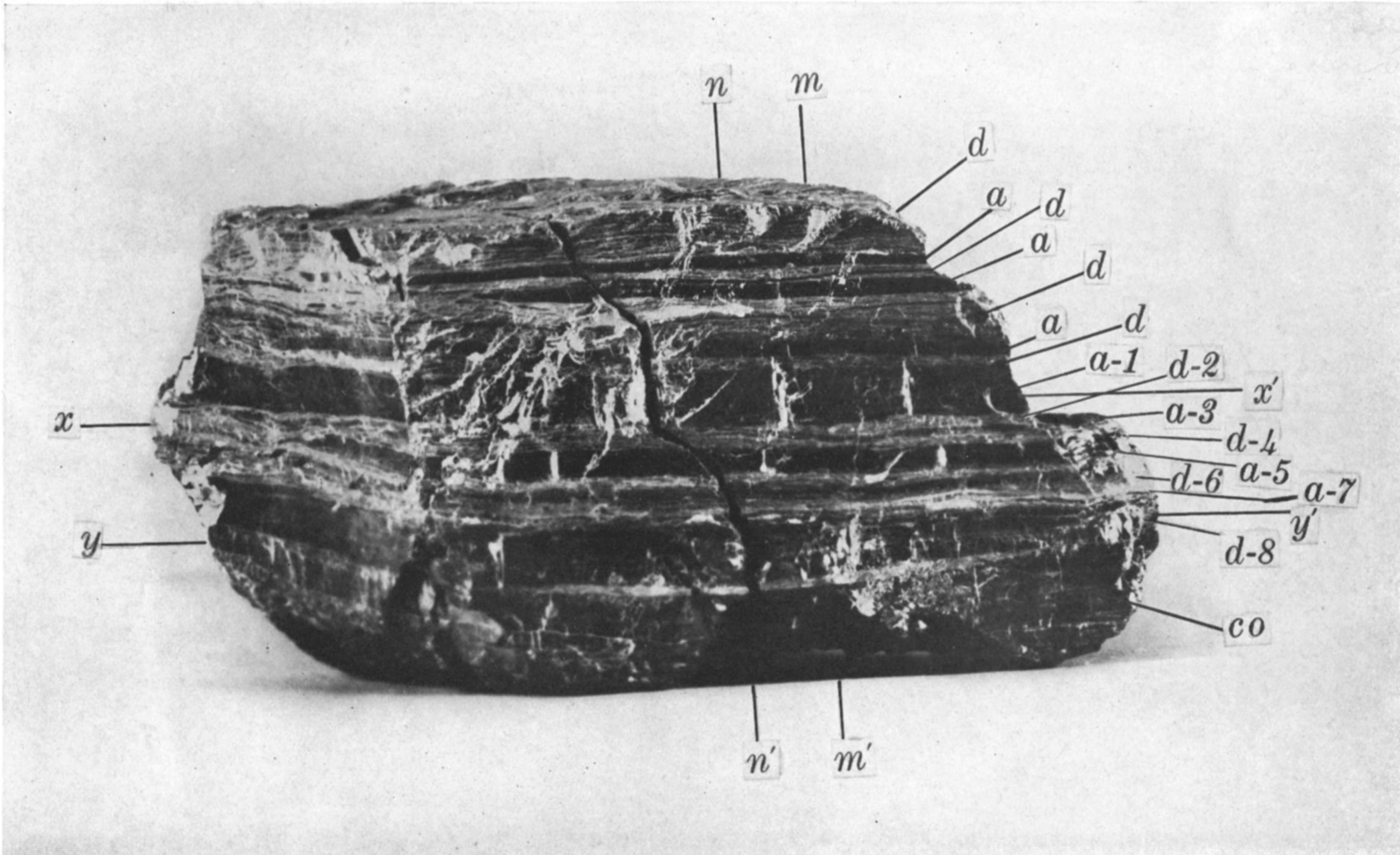
PLATE VI

FIG. 7.—Part of a thin cross-section of coal from Royalton, Illinois, at a low magnification, showing numerous thin chips of anthraxylon, more or less separated by thin layers of attritus. × 10.

FIG. 8.—A part of the thin section shown in Figure 1, at a higher magnification. Some of the anthraxylon chips have retained their cell structure to a remarkable degree, a common occurrence in most coals. × 200.

FIG. 9.—A part of a thin horizontal section of the coal from Ziegler, Illinois. A random section; the plant structure shown is of common occurrence in any horizontal section. Anthraxylon chips are seen on either side. The circular to oval spots in the attritus in the center represent spore-exines. × 150.

FIG. 10.—Part of a thin cross-section of the coal from Terre Haute, Indiana, at a low magnification. The numerous grayish bands or strips represent anthraxylon chips; the darker mottled matter between these represents the attritus. × 10.


n
m
d
a
d
a
d
a
d
a-1
d-2
x′
a-3
d-4
a-5
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co
x
y
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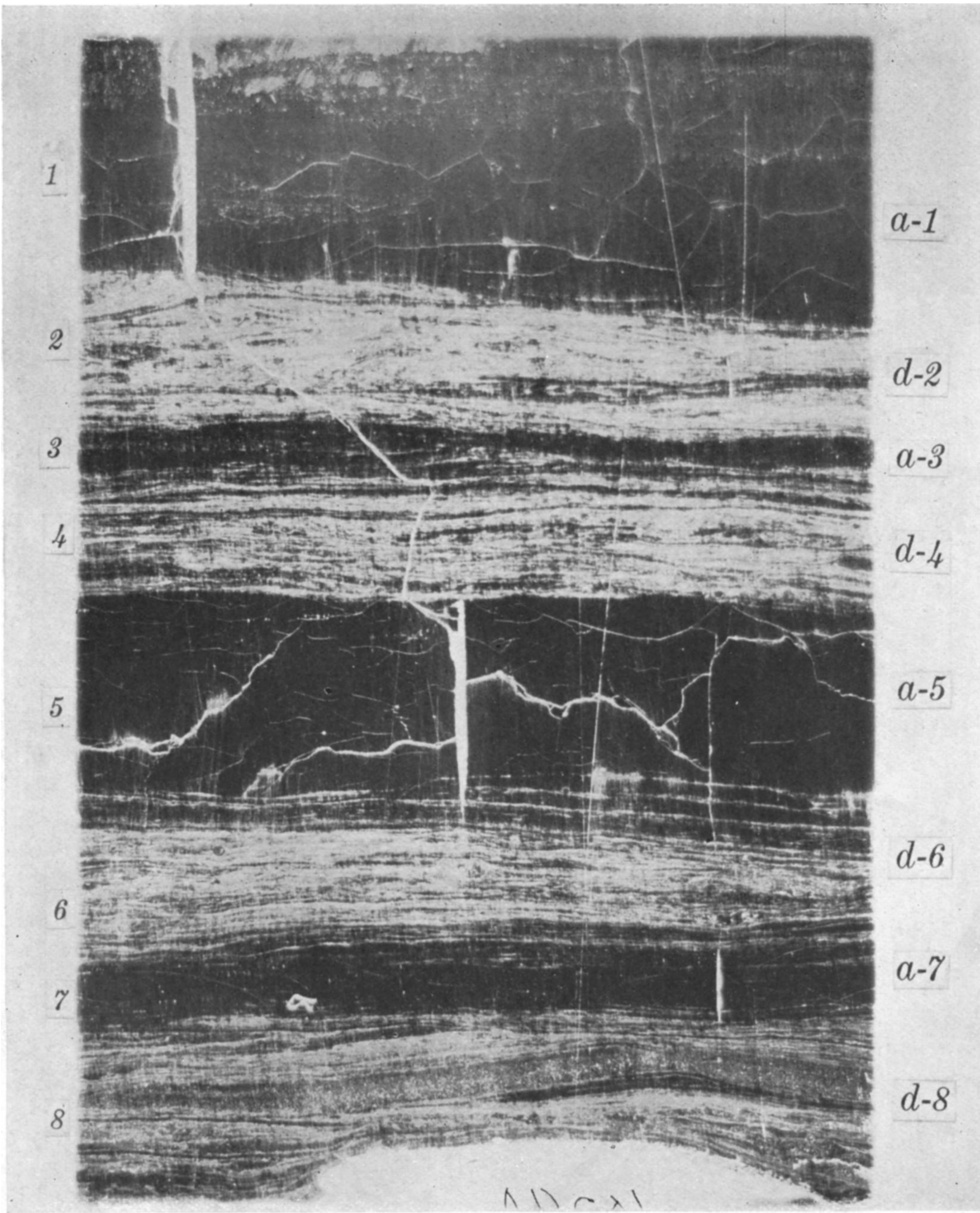
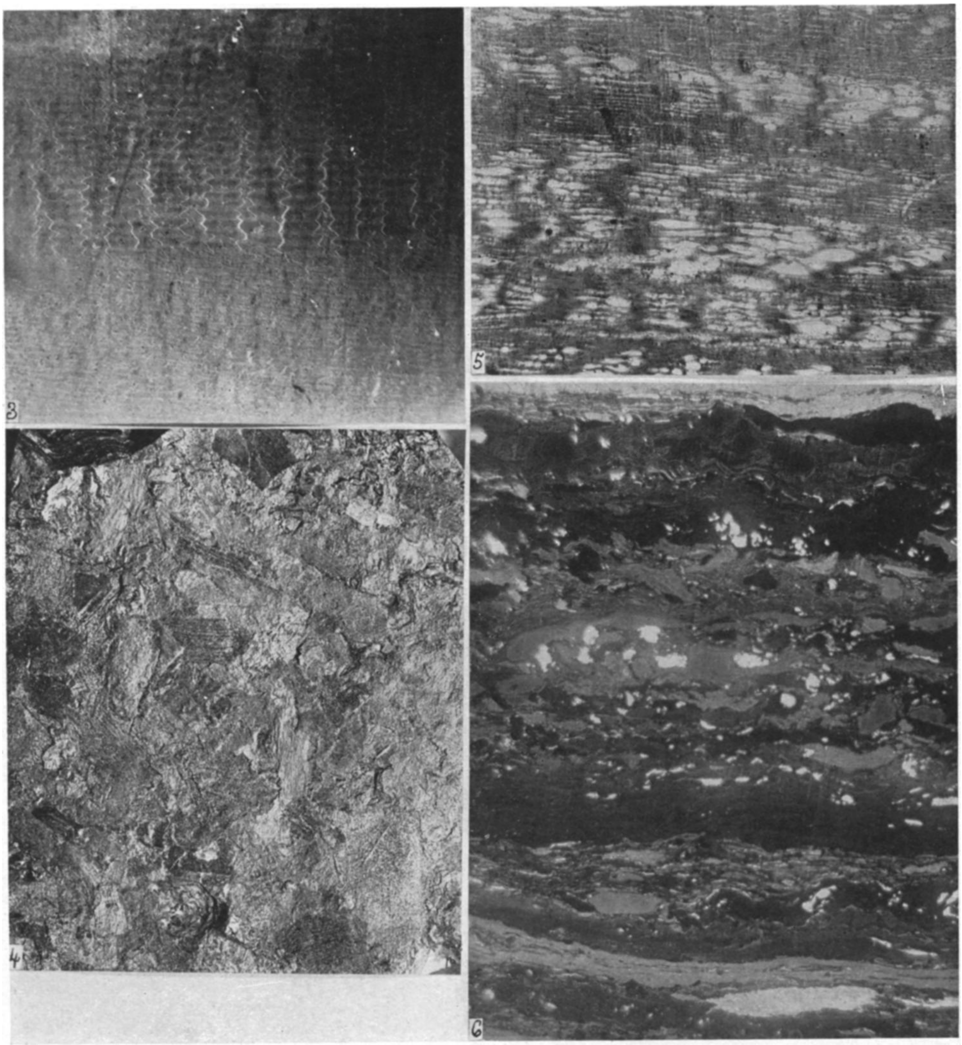
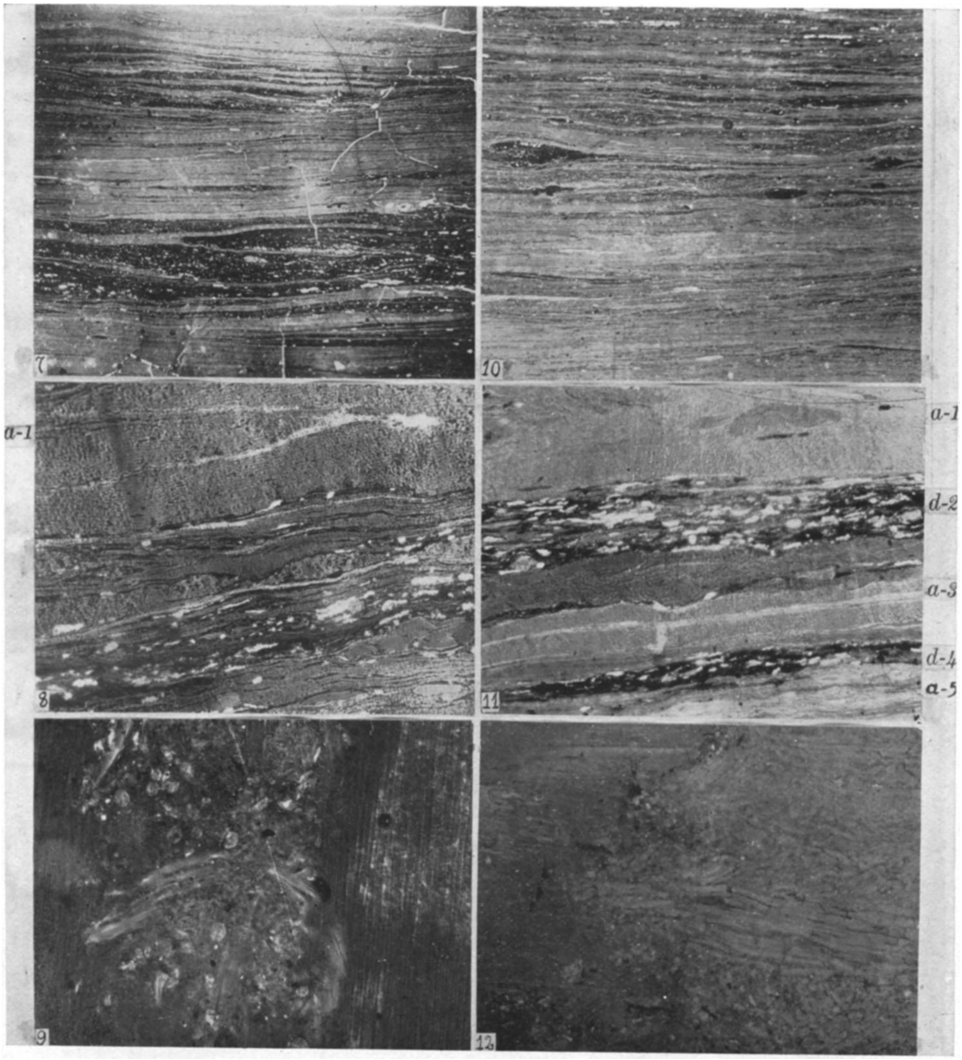


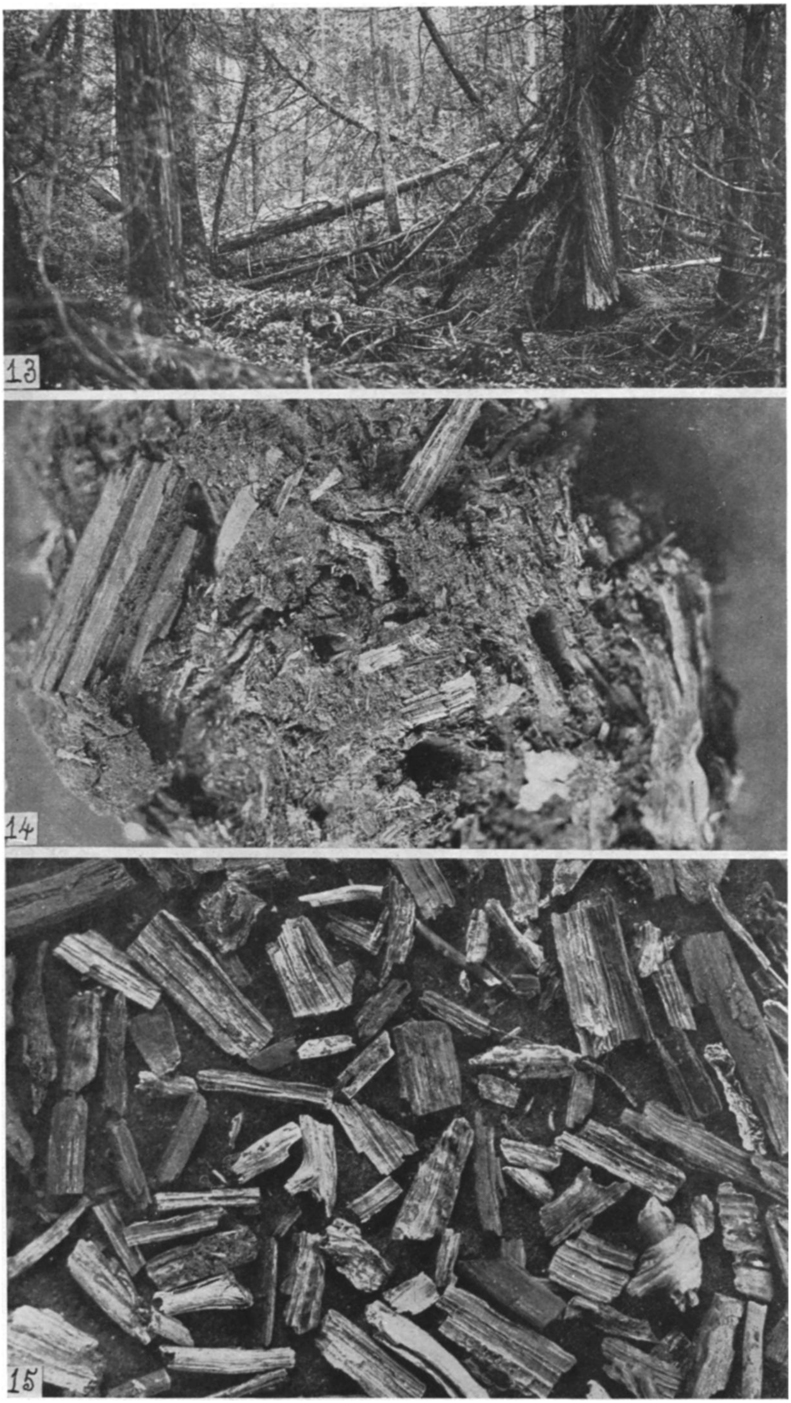
FIG. 2



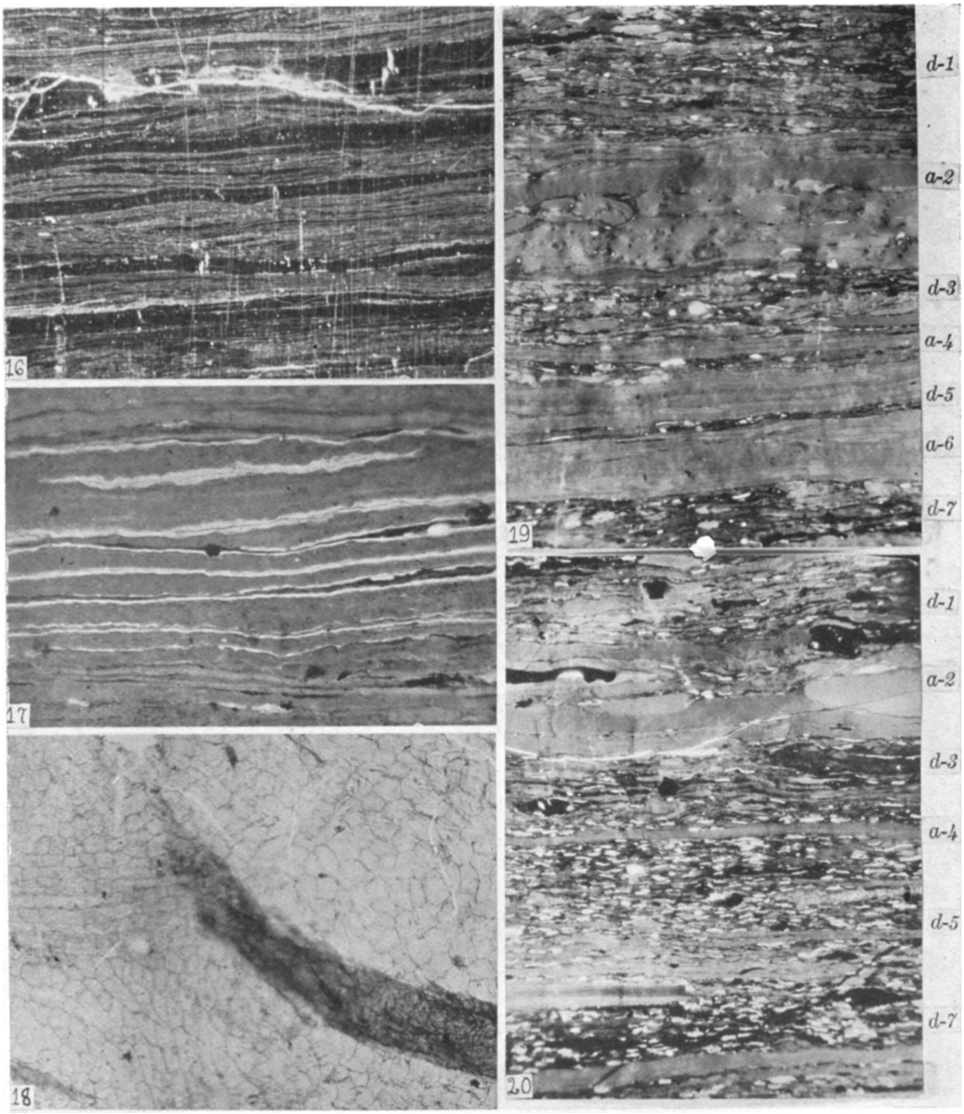
FIGS. 3–6



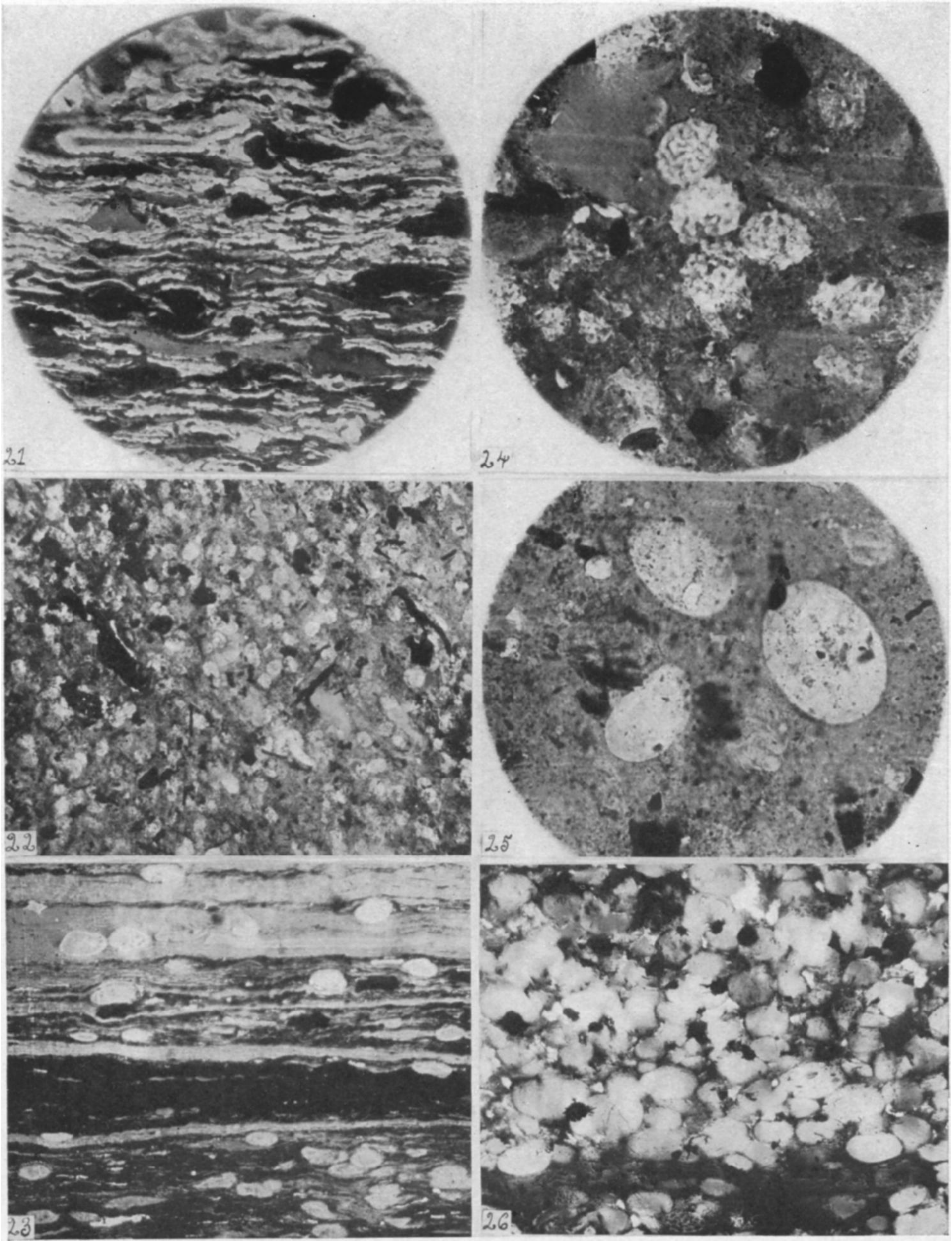
FIGS. 7–12



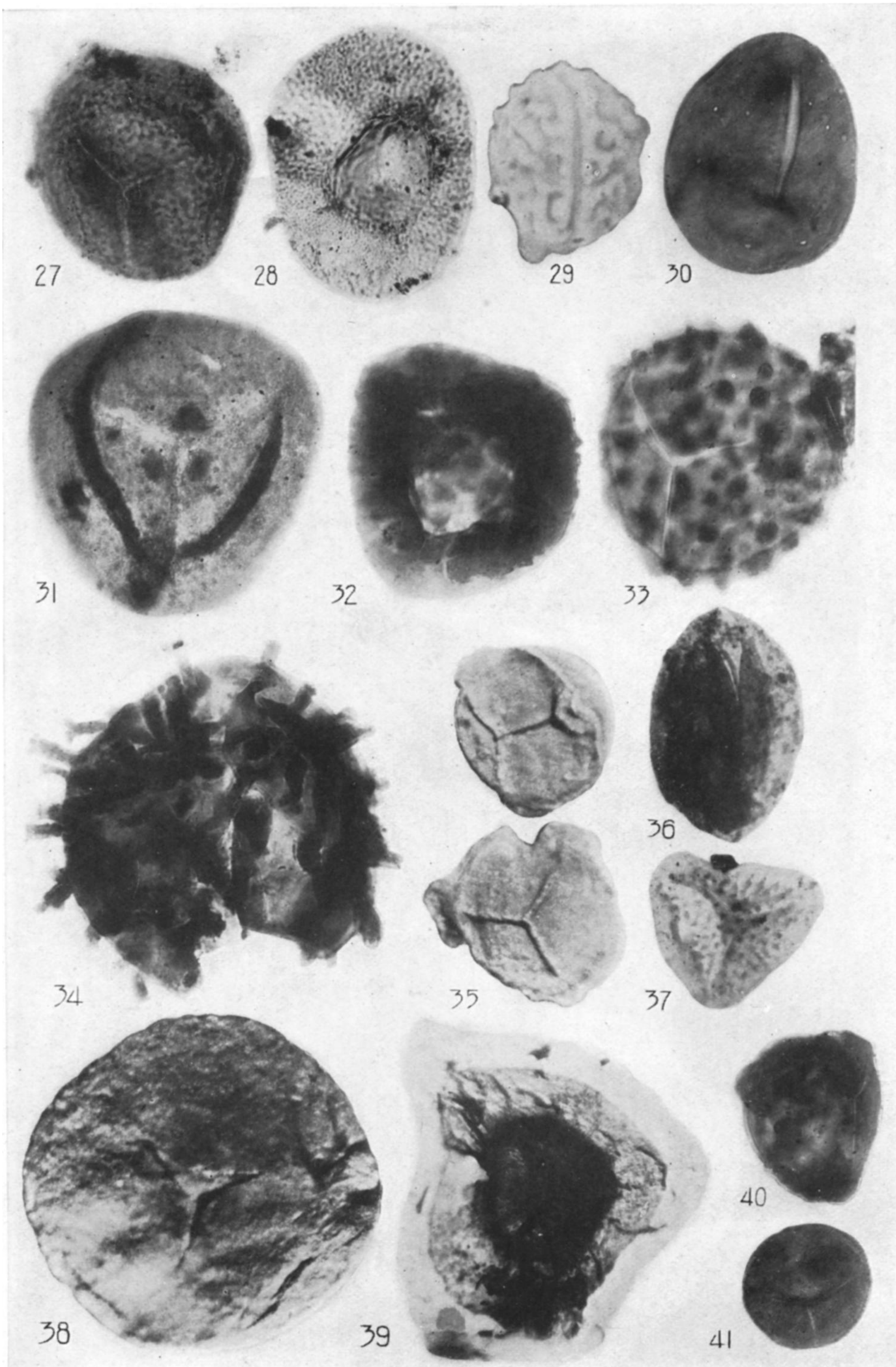
FIGS. 13–15



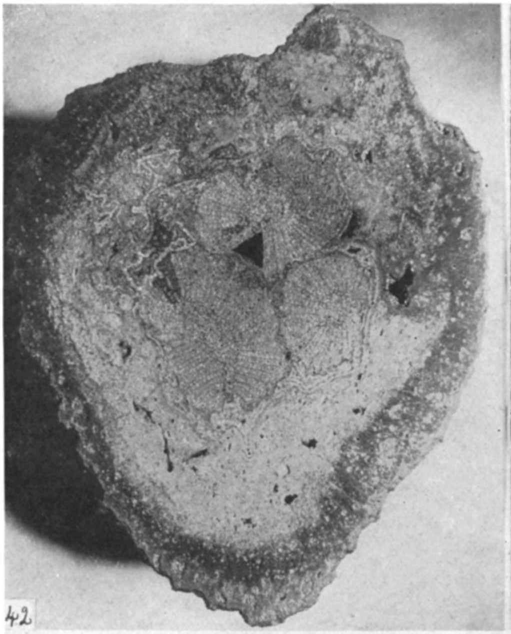
FIGS. 16–20



FIGS. 21–26



FIGS. 27–41



FIGS. 42–44

FIG. 11.—Part of the thin cross-section shown in Figure 5, at a higher magnification. *a*-1 is a thin anthraxylon chip, showing some plant structure; *d*-2, a thin sheet of attritus, containing a large amount of spore matter, some humic matter, and some earthy matter; *a*-3, anthraxylon chips; *d*-4, attritus. $\times$ 200.

FIG. 12.—Part of a thin horizontal section of coal from Terre Haute, Indiana. While the cross-sections reveal but very little plant or woody structure, every horizontal section shows a large amount of it, as in this section. $\times$ 150.

PLATE VII

FIG. 13.—A close-up view in a typical Wisconsin peat bog.

FIG. 14.—A lump of dried peat from the bog shown in Figure 13, showing thin chips of woody peat or anthraxylon, imbedded in the attritus. Compare this with Figure 4. Natural size.

FIG. 15.—The thin flat pieces of woody peat, picked out of the lump shown in Figure 14. Natural size.

PLATE VIII

FIG. 16.—Part of a thin cross-section of the coal from Ziegler, Illinois, containing a large proportion of cuticular matter. $\times$ 10.

FIG. 17.—Part of a thin cross-section of coal similar in appearance and composition as that shown in Figure 16. The heavy white lines running across the photograph represent leaf cuticles imbedded in matter largely derived from leaves. $\times$ 200.

FIG. 18.—One of the cuticles separated from the coal and seen flat-wise. $\times$ 200.

FIG. 19.—Part of a thin cross-section of a Pittsburgh coal with a number of thin anthraxylon strips. *d*-1, attritus rich in humic matter; *a*-2, thin anthraxylon strips rich in resinous matter; *d*-3, attritus; *a*-4, anthraxylon strips; *d*-5, thin layer of attritus; *a*-6, anthraxylon strip; *d*-7, attritus. Cell structures have been retained in *a*-4 and *a*-6. $\times$ 200.

FIG. 20.—Part of a thin cross-section of Pittsburgh coal rich in attritus. *d*-1, attritus composed of humic matter, spore-exines and carbonaceous matter. *a*-2, a thin anthraxylon layer; *d*-3 attritus composed of humic matter, spore-exines, and carbonaceous matter; *a*-4, a very thin strip of anthraxylon; *d*-5 and *d*-7, attritus, composed chiefly of spore-exines, some humic and carbonaceous matters, including thin strips of anthraxylon.

PLATE IX

FIG. 21.—Part of a thin cross-section of the coal from the Pittsburgh seam, at a very high magnification, showing the constituents in detail: spore-exines, in white; humic matter in gray; resinous particles, homogeneous gray, and carbonaceous matter in black. $\times$ 1,000.

FIG. 22.—Part of a thin horizontal section through a layer of attritus largely composed of spore matter, some humic matter, and some carbonaceous matter. The small circular to oval spots represent spore-exines; the irregular black spots, carbonaceous matter. × 150.

FIG. 23.—Part of a thin cross-section of coal, showing resinous particles in the anthraxylon and in the attritus.

FIG. 24.—Part of the thin horizontal section of Pittsburgh coal shown in Figure 22, at a very high magnification, showing the spore-exines and other constituents in detail. The spores are characteristic of the Pittsburgh bed. × 1,000.

FIG. 25.—Part of a thin horizontal section of coal from the Pittsburgh seam, at a very high magnification, showing the pollen grain type of spore-exines, imbedded in a matrix consisting of humic, carbonized, mineral, and earthy matter. × 1,000.

FIG. 26.—Part of a thin cross-section of anthraxylous coal from the Vandalia mine, Terre Haute, Indiana, showing a large number of oval resinous particles. The original woody issues have decayed in the part shown. × 200.

PLATE X

Spore-exines isolated from various coals by means of Schulze's reagent and seen flat-wise.

FIG. 27.—Spore-exine found in the coal from Buxton, Iowa. × 1,000.

FIG. 28.—Spore-exine predominant in and characteristic of the coal from Buxton, Iowa. × 1,000.

FIG. 29.—Spore-exine predominant in and characteristic of the Pittsburgh seam.

FIG. 30.—Exine of a pollen grain, common in all coals. × 1,000.

FIG. 31.—Spore-exine characteristic of and predominant in the coal from Shelbyville, Illinois. × 1,000.

FIG. 32.—Spore-exine characteristic of and predominant in the coal from the Sipsey mine, Alabama, Black Creek bed. × 1,000.

FIG. 33.—Spore-exine from bed No. 6, Illinois coal. × 1,000.

FIG. 34.—Spore-exines from an Illinois coal, bed No. 6. × 1,000.

FIG. 35.—Megaspore-exines of a smaller type, found in large numbers in the Shelbyville coal and occasionally in other coals. A megaspore similar to this but with three large air sacks is characteristic of coal from Buxton, Illinois. × 33.

FIG. 36.—Seedlike spore-exine from the Illinois coals, bed No. 6. × 100.

FIG. 37.—Spore-exine found in the coal from bed No. 5, Vandalia, Indiana. × 1,000.

FIG. 38.—Megaspore-exine predominant in the coal from Shelbyville, Illinois, but found occasionally in other coals. × 33.

FIG. 39.—Spore-exines, Spencerite type, common in all coals. × 100.

FIG. 40.—Spore-exine very common in the coal from Sessor, Illinois, but found in other coals from bed No. 6. × 1,000.

FIG. 41.—A spore-exine common in all coals.

PLATE XI

FIG. 42.—Cross-section of a pyritized fossil stem of Medullosa Anglica, showing three steles, surrounded by a common periderm; next to this is the inner cortex forming the outermost zone of tissues. The inner and outer cortexes are pervaded by leaf traces and gum ducts, both recognizable, though not distinctly in the photograph.

FIG. 43.—Part of a cleavage surface of coal, showing a large number of "rodlets" or "needles" imbedded helter-skelter in the attritus. × 10.

FIG. 44.—Part of a horizontal cleavage plane of coal showing a Medullosa type of woody structure, in which "needles" or "rodlets" form part of the tissue. × 3.